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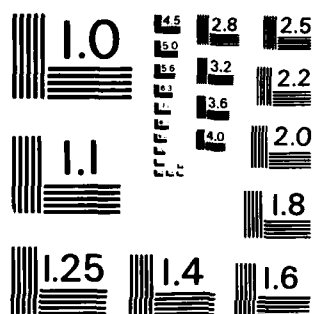
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TECHNICAL REPORT NO. 5

AD-A162 428

TIME-TEMPERATURE-TRANSFORMATION (TTT) CURE DIAGRAMS:

RELATIONSHIP BETWEEN $T_g$ AND THE TEMPERATURE AND TIME OF CURE

FOR EPOXY SYSTEMS

by

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for publication in

The Journal of Applied Polymer Science

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December 1985

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## REPORT DOCUMENTATION PAGE

| | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1 REPORT NUMBER<br>Technical Report #5 | 2 GOVT ACCESSION NO.<br>N/A | 3 RECIPIENT'S CATALOG NUMBER<br>N/A |
| 4 TITLE (and Subtitle)<br>Time-Temperature-Transformation (TTT) Cure Diagrams: Relationship Between $T_g$ and the Temperature and Time of Cure for Epoxy Systems. | | 5 TYPE OF REPORT & PERIOD COVERED<br>November 1984 – December 1985 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>X. Peng and J. K. Gillham | | 8. CONTRACT OR GRANT NUMBER(s)<br>N00014-84-K-0021 |
| 9 PERFORMING ORGANIZATION NAME AND ADDRESS<br>Polymer Materials Program<br>Department of Chemical Engineering<br>Princeton University, Princeton, NJ 08544 | | 10 PROGRAM ELEMENT PROJECT TASK<br>AREA & WORK UNIT NUMBERS |
| 11 CONTROLLING OFFICE NAME AND ADDRESS<br>Office of Naval Research<br>Attn: Code 413, 800 N. Quincy St.<br>Arlington, VA 22217 | | 12. REPORT DATE<br>December 1985 |
| | | 13 NUMBER OF PAGES<br>25 |
| 14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15 SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a DECLASSIFICATION DOWNGRADING SCHEDULE |

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18 SUPPLEMENTARY NOTES

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

| | |
|---|---|
| Cure | Kinetics |
| Epoxies | Time-Temperature Transformation Cure Diagrams |
| Vitrification | Vitrification |
| Glass Transition | |

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

A procedure is provided for estimating the time to full cure versus isothermal cure temperature for vitrified epoxy systems. An equation relating the glass transition temperature of vitrified epoxy systems to the time and temperature of cure is developed.

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SYNOPSIS

A procedure is provided for estimating the time to full cure versus isothermal cure temperature for vitrified epoxy systems. An equation relating the glass transition temperature of vitrified epoxy systems to the time and temperature of cure is developed.

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INTRODUCTION

The glass transition temperature, $T_g$, of a thermosetting system is observed to be higher than the temperature of cure, $T_{cure}$, after prolonged isothermal cure below the system's maximum glass transition temperature, $T_{g\infty}$ (1-7). This implies that the cure reactions proceed after $T_g$ has risen to $T_{cure}$ (i.e., after vitrification). It is therefore important to investigate the cure behavior after vitrification. This communication is concerned with the relationship between $T_g$, $T_{cure}$ and time of isothermal cure for two epoxy systems cured to beyond vitrification. The conclusions apply to both systems.

Linear $T_g$ - $T_{cure}$ relationships were obtained after cure at different temperatures for fixed times. The temperatures of cure for full cure to occur in the same fixed times could be obtained by extrapolation of the appropriate $T_g$ - $T_{cure}$ relationships to $T_{g\infty}$. The time to full cure versus $T_{cure}$ is presented in a time-temperature-transformation (TTT) cure diagram together with the times to gelation and to vitrification (1-7). An empirical $T_g$ - $T_{cure}$ - time equation is also developed. The two epoxy systems investigated were a difunctional and a trifunctional epoxy resin each cured with the same tetrafunctional aromatic diamine.

EXPERIMENTAL

Materials

The difunctional epoxy was a diglycidyl ether of bisphenol A (DER 331, Dow Chemical Co.), the trifunctional epoxy was the triglycidyl ether of tris(hydroxy phenyl)methane (XD 7342.00, Dow Chemical Co.), and the curing agent was trimethylene glycol di-p-aminobenzoate ("TMAB", Polacure 740M, Polaroid Corp.). Stoichiometric formulations were prepared on the basis of one epoxy group per amine hydrogen.

Cure, $T_g$, and $T_{g\times}$ Measurements

The epoxy resin systems were cured isothermally at different temperatures in a flowing atmosphere of dry helium in a torsional braid analysis (TBA) chamber (1). Each specimen was prepared using a multifilamented heated-cleaned glass braid impregnated with a solution of the reactants (1 g. solid/1 ml methyl-ethyl ketone). Changes due to cure were monitored as a function of time by measuring the frequency (~ 1 Hz) and decay of intermittently induced free oscillations; the times to gelation and to vitrification were located by maxima in the logarithmic decrement plots. Each specimen was cured for a pre-selected time, which was longer than the time to vitrification, at the temperature of cure, $T_{cure}$. After isothermal cure, dynamic mechanical spectra (~ 1 Hz) of the specimens were obtained on cooling from $T_{cure}$ to -180°C and then on heating, to 240°C for the DER 331/TMAB system and to 280°C for the XD/TMAB system, at a rate of 1.5°C/min. Spectra were then obtained on subsequent

cooling. The glass transition temperature, $T_g$, was identified by the temperature of the principal maximum in the logarithmic decrement plot during the heating scan. The maximum glass transition temperature, $T_{g\infty}$, was identified as the glass transition temperature during the subsequent cooling scan (from 240°C for DER 331/TMAB and from 280°C for XD/TMAB).

The data for $T_{g\infty}$ versus $T_{cure}$ for different cure times were compared (not shown). A small increase in $T_{g\infty}$ with increasing temperature of isothermal cure for DER 331/TMAB was observed. This behavior is attributed to the cure not being completed by heating to and cooling from 240°C after the isothermal cures. The $T_{g\infty}$ data for the XD/TMAB system followed a trend in which the higher values of $T_{g\infty}$ were obtained with high cure temperatures for short cure times, low cure temperatures for long cure times, and intermediate cure temperatures for intermediate cure times. This behavior could be attributed to the competition between cure (which increases $T_g$) and thermal degradation (which decreases $T_g$) at the high temperatures which are necessary for curing this high $T_{g\infty}$ system. Average values of $T_{g\infty}$ were used for the calculations in this paper: 168°C for the DER 331/TMAB system (range 166 to 170°C), and 268°C for the XD/TMAB system (range 261 to 278°C).

RESULTS AND DISCUSSION

$T_g$ vs. $T_{cure}$

The data for $T_g$ vs. $T_{cure}$ for the DER 331/TMAB and XD/TMAB systems for different times of isothermal cure are given in Tables 1 and 2, and are plotted as $T_g$ vs. $T_{cure}$ in Figures 1 and 2. A set of approximately parallel

lines was obtained for each system. Each line represents a linear relationship between $T_g$ and $T_{cure}$ for the same cure time (which was longer than the time to vitrification). Therefore

$$T_g = A + B \, T_{cure} \qquad (1)$$

where A depends on, and B is independent of, the cure time. The values of A and B for different cure times for the DER 331/TMAB and XD/TMAB systems are presented in Tables III and IV. The average values of B are 0.98 and 1.24 for the DER 331/TMAB system and the XD/TMAB system, respectively (ratio = 0.79). Also, the apparent activation energies, $\Delta E$, for full cure are 71.6 and 92.7 kcal/mol for the DER 331/TMAB and the XD/TMAB systems, respectively (ratio = 0.78) (see later, Table 7). It is possible therefore that the slope, B, is related to the activation energy and hence to the reaction mechanism. Since the cure reaction for the XD/TMAB system has the higher activation energy after vitrification, the effect of increasing $T_{cure}$ on $T_g$ (which increases with the extent of cure) is greater for the XD/TMAB system than for the DER 331/TMAB system.

## $T_{cure}$ vs. Time to Full Cure

Assuming that the materials are fully cured when $T_g$ reaches $T_{g\infty}$, the temperature for full cure to occur in a specified time, $T_\infty(t)$, was determined by extrapolation of the $T_g$ - $T_{cure}$ relationship line for the same cure time to $T_{g\infty}$ using equation 1. For example, since for the XD/TMAB system $T_g = -2.67 + 1.20 \, T_{cure}$ for the sixty minute cure time, then when $T_g = T_{g\infty} = 268°C$, $T_{cure} = $

$T_x(60) = 226°C$. In other words, the time to full cure at the cure temperature of 226°C, $t_{x(226)}$, should be 60 minutes. Times to full cure, $t_x$, at different cure temperatures were calculated in this manner. They are presented in Table 5.

For testing the extrapolated conditions for obtaining full cure shown in Table 5, the DER 331/TMAB system was cured at 148°C/1440 min, 146°C/2880 min, and 141°C/8640 min, and the XD/TMAB system was cured at 211°C/1440 min, and 207°C/2880 min. The corresponding values of $T_g$ obtained from these cure conditions for the DER 331/TMAB system were 165°C, 166°C, and 166°C, and for the XD/TMAB system were 268°C and 265°C (Figures 1 and 2). They are close to, but in general below, the average values of $T_{gx}$ for the DER 331/TMAB system (168°C) and for the XD/TMAB system (268°C).

If the extrapolated data for $T_{cure}$ versus time to full cure (Table 5) are plotted as $T_{cure}$ vs. log time of cure, a new line results which is designated the full cure line on a Time-Temperature-Transformation (TTT) cure diagram (Figure 3). The gelled glass region in the TTT diagram is divided into two parts by the full cure line. In the absence of degradation (Figure 3, devitrification and char formation), the top and lower parts could be designated fully cured gelled glass (gel glass) and undercured gelled glass (sol/gel glass) regions, respectively. The TTT diagrams with the full cure lines for the DER 331/TMAB system and for the XD/TMAB system are shown in Figures 4 and 5, respectively. These lines appear to be linear, which can therefore be expressed by

$$T_x = a + b \log t_x \tag{2}$$

where $T_x$ and $t_x$ are the temperature and time to full cure, respectively. The intercepts (a) and slopes (b) for the two systems are provided in Table 6. The full cure line should be useful for designing cure processes which lead to full cure. Selection of the temperature or time of cure gives the time or temperature, respectively, to full cure.

The data for the extrapolated time to full cure versus temperature of isothermal cure for the two systems are plotted in an Arrhenius manner as the logarithmic time versus 1/T(K) in Figure 6, which also includes corresponding data for gelation and vitrification. The activation energies for full cure (after vitrification), gelation, and vitrification for the DER 331/TMAB and the XD/TMAB systems are presented in Table 7. That the activation energy for full cure is much higher than that for gelation is a result of the cure reactions being controlled by physical relaxations in the glassy state (which themselves have similarly high activation energies).

## $T_g$ - $T_{cure}$ - Time Equation

An equation relating $T_g$, $T_{cure}$ and time of cure can be derived from equations 1 and 2. From equation 1, with $T_g = T_{gx}$ and $T_{cure} = T_x$,

$$T_{gx} = A + B T_x \tag{3}$$

For cure in the same time period, subtracting equation 1 from equation 3 results in

$$T_g - T_g = B(T_x - T_{cure})  \qquad (4)$$

Substituting for $T_x$ in equation 4 in terms of time using equation 2 gives

$$T_{gx} - T_g = B(a + b \log t_x - T_{cure})  \qquad (5)$$

where $t_x$ could be any time, $t$.

Therefore equation 5 can be rewritten as

$$T_g = T_{gx} - B(a + b \log t - T_{cure})  \qquad (6)$$

The $T_g$ of the material cured at temperature $T_{cure}$ for time $t$ can be calculated using this $T_g - T_{cure}$ - time equation.

The particular equations for the DER 331/TMAB and the XD/TMAB systems were formulated by substituting values for $T_{gx}$, B, a, and b in equation 6 with the data in Tables 3-6. For the DER 331/TMAB system,

$$T_g = 10.18 \log t + 0.98 T_{cure} - 10  \qquad (7)$$

and for the XD/TMAB system,

$$T_g = 14.48 \log t + 1.24 T_{cure} - 36  \qquad (8)$$

where $t$ is in minutes, and $T_{cure}$ and $T_g$ are in degrees centigrade.
For both systems, the $T_g$ calculated ($T_g$ cal) by equations 7 and 8 are included in Tables 1 and 2 together with the corresponding experimental values for $T_g$. The agreement is good.

For an approximate calculation of $T_g$ from $T_{cure}$ and cure time for the epoxy systems, only two $T_g$ vs. $T_{cure}$ lines for two specified cure times are

needed if $T_g$, is known. The parameters B, a and b in equation 6 can be derived
from these two lines. This procedure is a simple one for obtaining the rela-
tionship between $T_g$, $T_{cure}$ and time of cure.

## Correction of Cure Time

The relationship between $T_g$ and $T_{cure}$ for the same isothermal cure time
observed in this work is for cure behavior after vitrification since the cure
behavior after vitrification, where the cure reaction proceeds in the glassy
state, should be different from that before vitrification where the cure
reaction occurs in the liquid and rubbery states. This suggests that the time
of cure should be measured from the vitrification time and that the time of
cure in this work should be corrected by subtracting the vitrification time.
For example, when the DER 331/TMAB system was cured at lower temperatures, the
data points deviated from the straight line (Figure 1); presumably for shorter
times the data would also deviate from linearity. They would be expected to
be closer to the straight line if the times of cure were corrected. For the
XD/TMAB system, the errors were less because the time to vitrification for the
XD/TMAB system was shorter than for the DER 331/TMAB system. Similarly,
correcting the time of cure would be expected to reduce the difference between
the test values of $T_g$ and the average value of $T_{g\alpha}$ (Figures 1 and 2). As a
quantitative example, a sample of the DER331/TMAB system was cured at 165°C
for 39 minutes which according to equation 2 should give full cure. The
observed $T_g$ of 117°C was much lower than $T_{g\alpha}$ (168°C). However, the observed
$T_g$ was 167°C when cure at 165°C was for the time to vitrification (351 minu-
tes) plus 39 minutes.

CONCLUSIONS

Analysis of the relationships between the time and temperature of cure for two epoxy systems has led to the following conclusions for both systems.

1. A linear $T_g$ - $T_{cure}$ relationship for isochronal cure was observed.

2. The cure temperature for full cure to occur in a given cure time can be determined by extrapolation of the appropriate $T_g$ - $T_{cure}$ line to $T_{g\infty}$. A plot of $T_{cure}$ versus log time of cure to full cure yields a new line, the full cure line, on the time-temperature-transformation (TTT) cure diagram.

3. The apparent activation energies for full cure, and for gelation and vitrification, were obtained from their Arrhenius relationships. The activation energy for full cure is much higher than those for gelation and vitrification as a consequence of the cure reactions being controlled by physical relaxations in the glassy state.

4. An empirical $T_g$ - $T_{cure}$ -time equation for cure in the vitrified state has been developed which permits computation of the glass transition temperature from the temperature and time of cure.

ACKNOWLEDGMENTS

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TABLE CAPTIONS

1.    $T_g$ vs. $T_{cure}$ for Specified Times of Cure for the DER 331/TMAB System.

2.    $T_g$ vs. $T_{cure}$ for Specified Times of Cure for the XD/TMAB System.

3.    $T_g = A + B\ T_{cure}$:  Values of A and B for the DER 331/TMAB System.

4.    $T_g = A + B\ T_{cure}$:  Values of A and B for the XD/TMAB System.

5.    Time to Full Cure versus Cure Temperature for the DER 331/TMAB

      and XD/TMAB Systems.

6.    $T_x = a + b\ \log t_x$:  Full Cure Line Parameters for the DER 331/TMAB and

      the XD/TMAB Systems.

7.    Apparent Activation Energies for the Isothermal Transformations of the

      DER 331/TMAB and the XD/TMAB Systems.

FIGURE CAPTIONS

1. $T_g$ vs. $T_{cure}$ for the DER 331/TMAB System for Preselected Times of Cure (Solid Lines):

   ($\bigtriangledown$) 720 min, (■) 1440 min; (□) 2880 min; (○) 5760 min; (▲) 8640 min; (o) 23040 min. Extrapolated values to $T_{g\infty}$ of $T_g$ vs. $T_{cure}$ (•). Also: experimental test values of $T_g$ (■, □, and ▲) from the extrapolated values of $T_{cure}$ (see text). Also included is the line for the average value of $T_{g\infty}$, and the $T_g$ = $T_{cure}$ line (which is not for constant time).

2. $T_g$ vs. $T_{cure}$ for the XD/TMAB System for Preselected Times of Cure (Solid Lines):

   ($\nabla$) 60 min; (■) 300 min; (□) 1440 min; (○) 2880 min; (Δ) 5760 min; (o) 14440 min. Extrapolated values to $T_{g\infty}$ of $T_g$ vs. $T_{cure}$ (•). Also: experimental test values of $T_g$ (□ and ○) from the extrapolated values of $T_{cure}$ (see text). Also included is the line for the average value of $T_{g\infty}$, and the $T_g$ = $T_{cure}$ line (which is not for constant time).

3. Schematic Isothermal Time-Temperature-Transformation (TTT) Cure Diagram Displaying Temperature of Cure, $T_{cure}$, vs. Times to Gelation, Vitrification, Full Cure and Char Formation. The full cure line ($T_g$ = $T_{g\infty}$) is constructed so as to connect the physically controlled relationship in the glassy state with the chemically controlled relationship above $T_{g\infty}$.

4. TTT Cure Diagram for the DER 331/TMAB System: (■) Gelation (experimental); (o) Vitrification (experimental); (▲) Full Cure (calculated, see text).

5. TTT Cure Diagram for the XD/TMAB System: (●) Gelation (experimental); (o) Vitrification (experimental); (▲) Full Cure (calculated, see text).

6. Ln Time (min) vs. 1/T(K) for the DER 331/TMAB System: (∇) Gelation; (■) Vitrification; (□) Full Cure. Also Ln Time (min) vs. 1/T(K) for the XD/TMAB System: (◯) Gelation; (▲) Vitrification; (o) Full Cure. Activation energies were obtained from the regions of linear data (solid lines).

TABLE 1. $T_g$ vs. $T_{cure}$ for Specified Times of Cure for the DFR 331/TMAB System

| Cure Time | 720 min | | | | | 1440 min | | | | | 2880 min | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{cure}$, °C | 110 | 120 | 135 | 140 | 150 | 100 | 110 | 120 | 135 | 140 | 100 | 110 | 120 | 135 |
| $T_g$, °C[1] | 123 | 137 | 151 | 156 | 164 | 119 | 131 | 143 | 155 | 159 | 126 | 135 | 145 | 158 |
| $T_g$ cal, °C[2] | 127 | 137 | 151 | 156 | 156 | 120 | 130 | 140 | 154 | 159 | 123 | 133 | 143 | 156 |

| Cure Time | 5760 min | | | | 8640 min | | | | 23040 min | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{cure}$, °C | 80 | 100 | 120 | 135 | 80 | 100 | 120 | 135 | 80 | 100 | 120 |
| $T_g$, °C[1] | 105 | 128 | 147 | 160 | 107 | 130 | 148 | 161 | 113 | 134 | 152 |
| $T_g$ cal, °C[2] | 107 | 126 | 146 | 161 | 109 | 128 | 148 | 162 | 113 | 132 | 152 |

1 Measured values

2 Calculated values

TABLE 2. $T_g$ vs. $T_{cure}$ for Specified Times of Cure for the XD/TMAR System

| Cure Time | 60 min | | | 300 min | | | | 1440 min | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{cure}$, °C | 180 | 200 | 220 | 150 | 180 | 195 | 200 | 90 | 120 | 150 | 180 | 195 |
| $T_g$, °C[1] | 213 | 238 | 261 | 184 | 219 | 241 | 245 | 119 | 158 | 191 | 229 | 249 |
| $T_g$ cal, °C[2] | 211 | 236 | 261 | 184 | 221 | 240 | 246 | 119 | 157 | 194 | 231 | 250 |

| Cure Time | 2880 min | | | | | 5760 min | | | | | 14400 min | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{cure}$, °C | 90 | 120 | 150 | 180 | 195 | 90 | 120 | 150 | 180 | 195 | 80 | 150 | 190 |
| $T_g$, °C[1] | 123 | 162 | 195 | 234 | 254 | 127 | 167 | 198 | 239 | 259 | 119 | 203 | 260 |
| $T_g$ cal, °C[2] | 124 | 161 | 198 | 235 | 254 | 128 | 165 | 202 | 240 | 258 | 121 | 208 | 258 |

1 Measured values

2 Calculated values

TABLE 3.  $T_g = A + B\ T_{cure}$: Values of A and B for the DER 331/TMAB System

| Cure Time | 720 min | 1440 min | 2880 min | 5760 min | 8640 min | 23040 min |
|-----------|---------|----------|----------|----------|----------|-----------|
| A | 13.40 | 21.70 | 34.09 | 26.49 | 30.36 | 35.50 |
| B[a] | 1.01 | 0.99 | 0.92 | 1.00 | 0.98 | 0.98 |
| r[b] | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |

a  Average value of B = 0.98

b  Correlation coefficient

TABLE 4.  $T_g = A + B\ T_{cure}$: Values of A and B for the XD/TMAB System

| Cure Time | 60 min | 300 min | 1440 min | 2880 min | 5760 min | 14400 min |
|-----------|--------|---------|----------|----------|----------|-----------|
| A | -2.67 | -2.56 | 9.27 | 11.01 | 15.45 | 15.84 |
| B[c] | 1.20 | 1.24 | 1.22 | 1.24 | 1.24 | 1.27 |
| r[d] | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

c  Average value of B = 1.24

d  Correlation coefficient

TABLE 5. Time to Full Cure versus Cure Temperature for the DER 331/TMAB and XD/TMAB Systems.

| System | DER 331/TMAB ($T_{g\alpha}$ = 168°C) | | | | | | XD/TMAB ($T_g$ = 268°C) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{cure}$, °C | 152 | 148 | 146 | 142 | 141 | 136 | 226 | 218 | 211 | 207 | 203 | 198 |
| 1/Tx1000,°K | 2.35 | 2.38 | 2.39 | 2.41 | 2.42 | 2.45 | 2.00 | 2.04 | 2.07 | 2.08 | 2.10 | 2.12 |
| $t_x$, min | 720 | 1440 | 2880 | 5760 | 8640 | 23040 | 60 | 300 | 1440 | 2880 | 5760 | 14400 |

TABLE 6. $T_x = a + b \log t_x$: Full Cure Line Parameters for the DER 331/TMAB and the XD/TMAB Systems

| System | Intercept (a) | Slope (b) | Correlation Coefficient |
|---|---|---|---|
| DER 331/TMAB | 181.47 | -10.39 | 0.99 |
| XD/TMAB | 247.11 | -11.68 | 1.00 |

TABLE 7. Apparent Activation Energies for Isothermal Transformations
for DER331/TMAE and the XD/TMAB Systems

| System | $\Delta E^1$ Gelation | $\Delta E^{1,2}$ Vitrification | $\Delta E^1$ Full Cure |
|---|---|---|---|
| DER331/TMAB | 13.6 | 9.2 | 71.6 |
| XD/TMAB | 13.7 | 10.9 | 92.7 |

1) $\Delta E$ in kcal/mole.

2) $\Delta E$ for vitrification determined from the linear region of
   vitrification curve (Fig. 6).
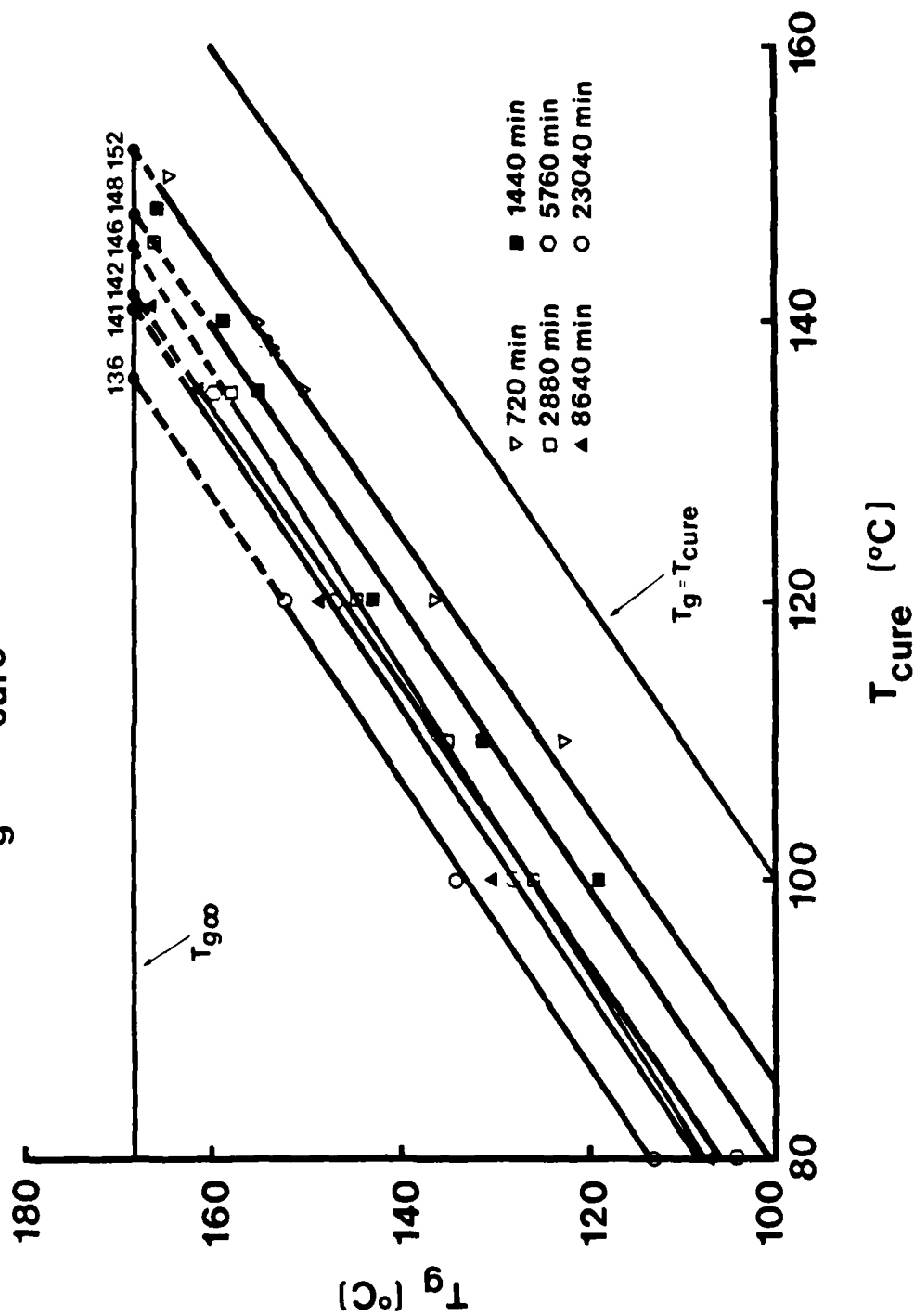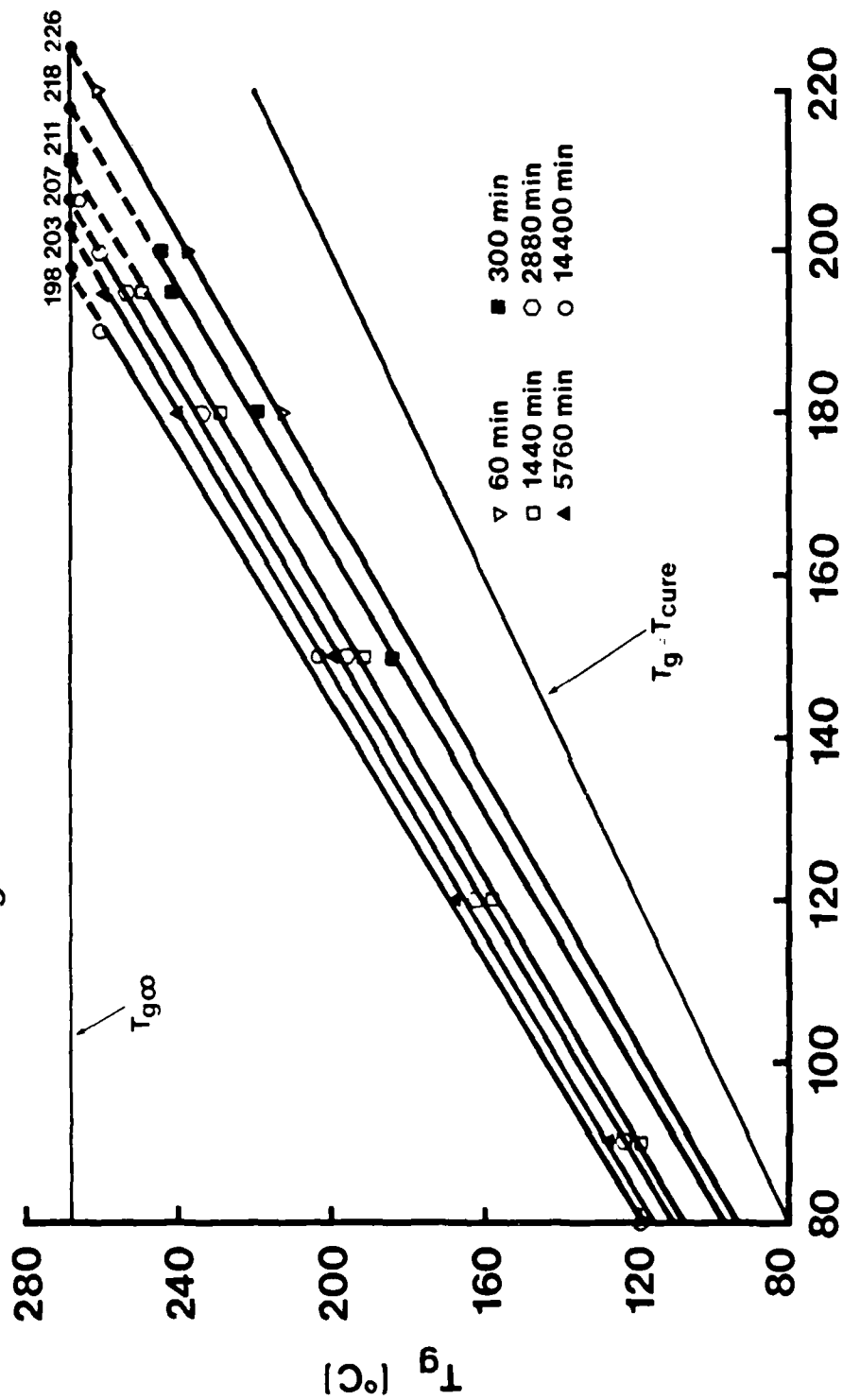
$T_g$ vs. $T_{cure}$ FOR DER331/TMAB

$T_{cure}$ [°C]

Fig. 1

# $T_g$ vs. $T_{cure}$ FOR XD/TMAB

Fig. 2

# THE THERMOSETTING PROCESS:
## TIME–TEMPERATURE–TRANSFORMATION CURE DIAGRAM



CHAR

ELASTOMER

SOL/GEL RUBBER

GELATION

FULL CURE

DEVITRIFICATION

VITRIFICATION

GELLED GLASS

LIQUID

UNGELLED GLASS

$T_{g\infty}$

gel $T_g$

$T_{go}$

TEMPERATURE, $T_{cure}$
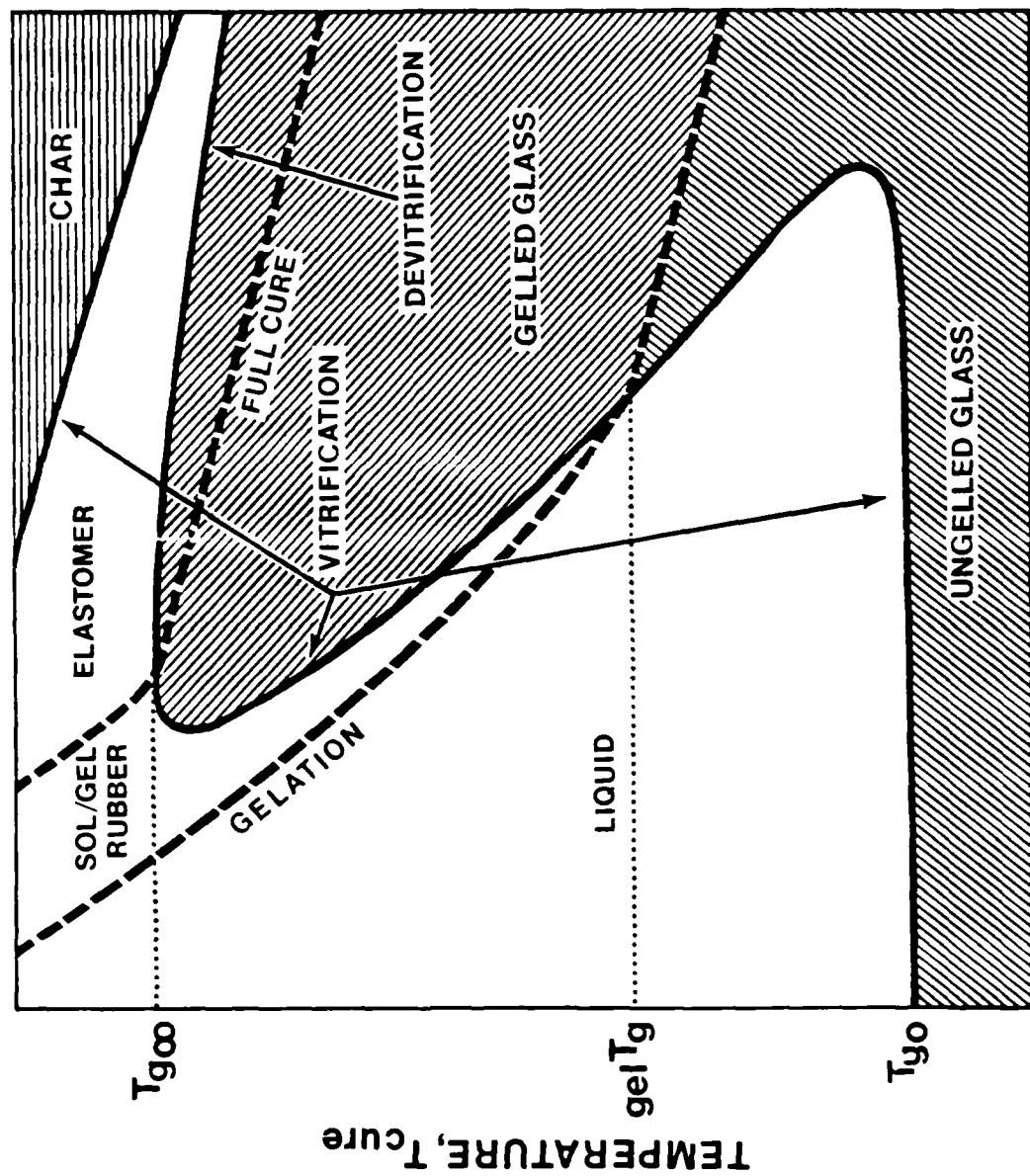
Fig. 3

# TTT DIAGRAM OF DER331/TMAB
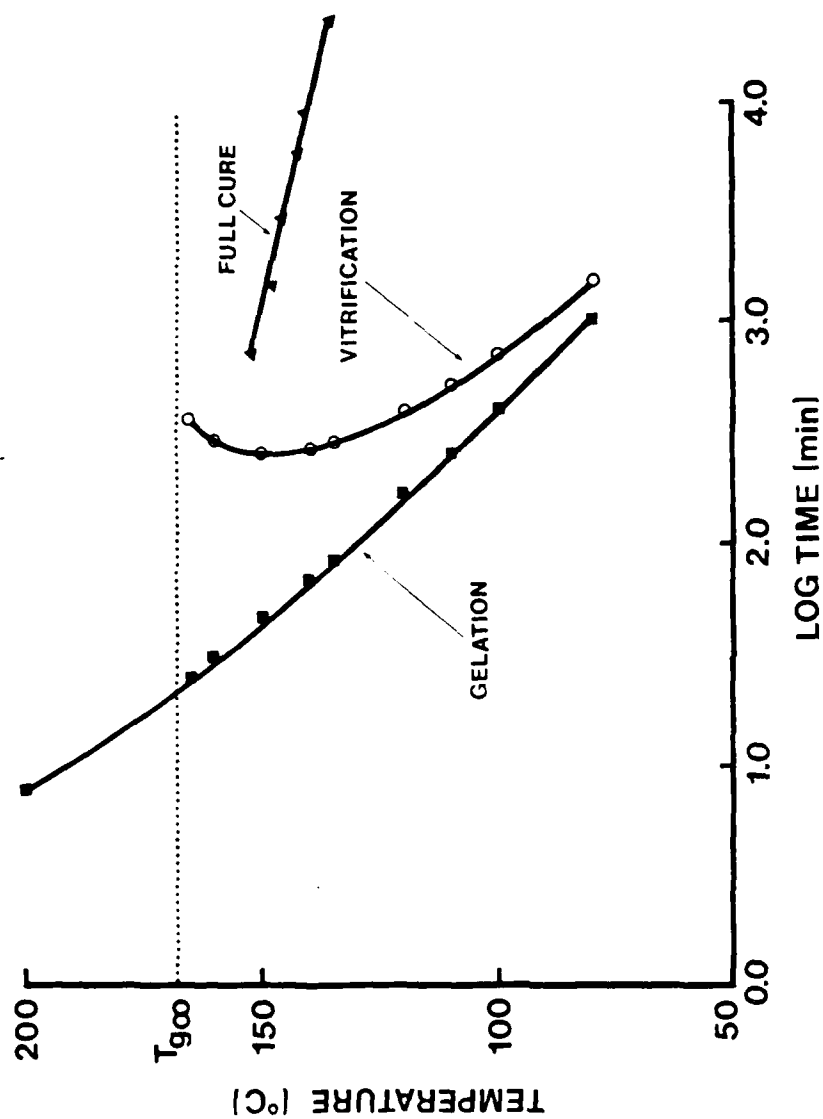


Fig. 4

TTT DIAGRAM OF XD/TMAB

FULL CURE

VITRIFICATION

GELATION

TEMPERATURE [°C]

300

$T_{g\infty}$ 250

200

150

100

50

LOG TIME [min]

0.0  1.0  2.0  3.0  4.0
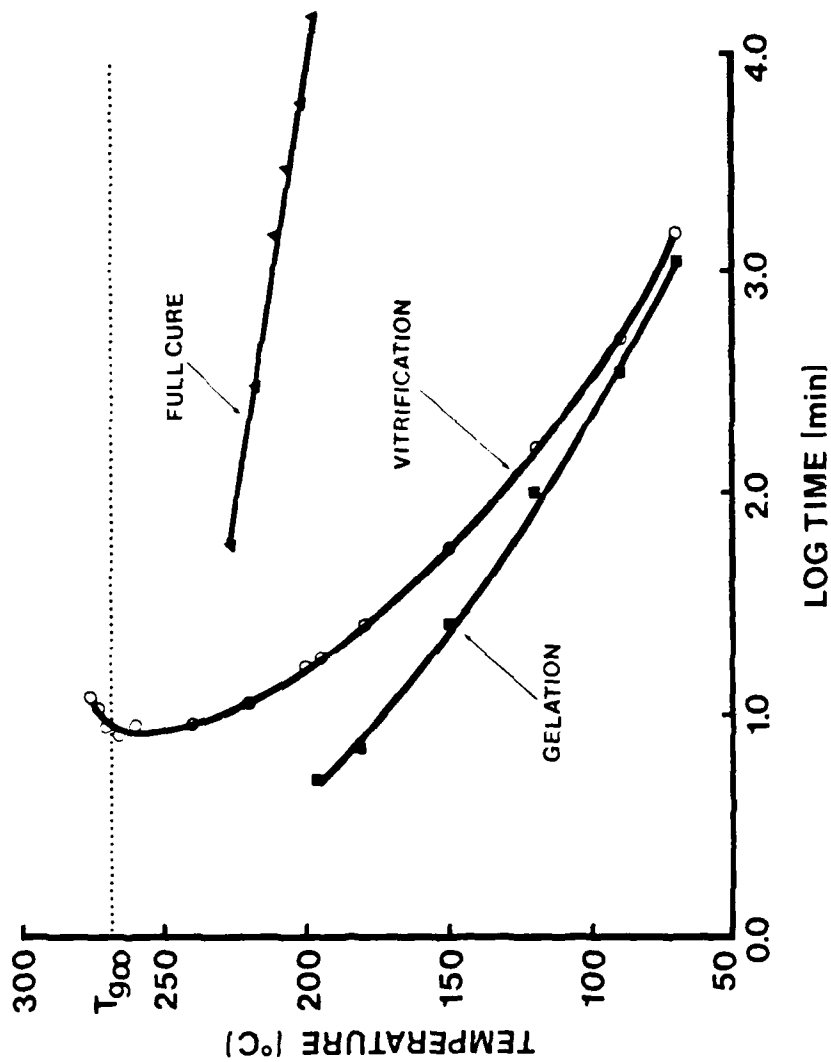
Fig. 5

Ln TIME vs. 1/T FOR
DER331/TMAB AND XD/TMAB

Ln TIME (min)

1000/T [K]

DER331/TMAB
▽ Gelation
■ Vitrification
□ Full Cure

XD/TMAB
○ Gelation
▲ Vitrification
○ Full Cure
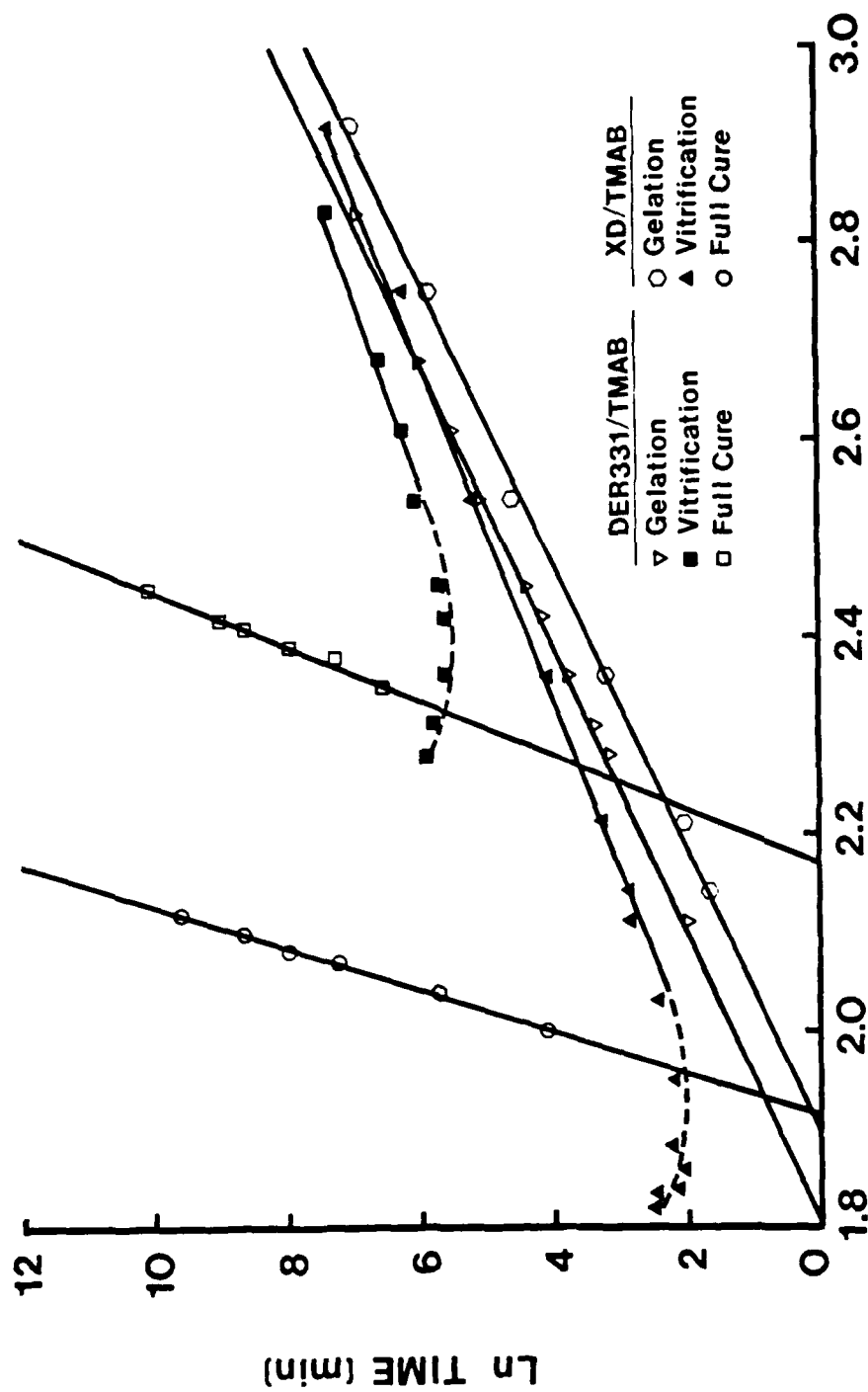
Fig. 6

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$$T_x = a + b \log t_x \tag{2}$$

where $T_x$ and $t_x$ are the temperature and time to full cure, respectively. The intercepts (a) and slopes (b) for the two systems are provided in Table 6. The full cure line should be useful for designing cure processes which lead to full cure. Selection of the temperature or time of cure gives the time or temperature, respectively, to full cure.

The data for the extrapolated time to full cure versus temperature of isothermal cure for the two systems are plotted in an Arrhenius manner as the logarithmic time versus $1/T(K)$ in Figure 6, which also includes corresponding data for gelation and vitrification. The activation energies for full cure (after vitrification), gelation, and vitrification for the DER 331/TMAB and the XD/TMAB systems are presented in Table 7. That the activation energy for full cure is much higher than that for gelation is a result of the cure reactions being controlled by physical relaxations in the glassy state (which themselves have similarly high activation energies).

## $T_g$ - $T_{cure}$ - Time Equation

An equation relating $T_g$, $T_{cure}$ and time of cure can be derived from equations 1 and 2. From equation 1, with $T_g = T_{g\lambda}$ and $T_{cure} = T_x$,

$$T_{g\alpha} = A + B T_x \tag{3}$$

For cure in the same time period, subtracting equation 1 from equation 3 results in

$$T_{g_x} - T_g = B(T_x - T_{cure}) \qquad (4)$$

Substituting for $T_x$ in equation 4 in terms of time using equation 2 gives

$$T_{g_x} - T_g = B(a + b \log t_x - T_{cure}) \qquad (5)$$

where $t_x$ could be any time, t.

Therefore equation 5 can be rewritten as

$$T_g = T_{g_x} - B(a + b \log t - T_{cure}) \qquad (6)$$

The $T_g$ of the material cured at temperature $T_{cure}$ for time t can be calculated using this $T_g$ - $T_{cure}$ - time equation.

The particular equations for the DER 331/TMAB and the XD/TMAB systems were formulated by substituting values for $T_{g_x}$, B, a, and b in equation 6 with the data in Tables 3-6. For the DER 331/TMAB system,

$$T_g = 10.18 \log t + 0.98 T_{cure} - 10 \qquad (7)$$

and for the XD/TMAB system,

$$T_g = 14.48 \log t + 1.24 T_{cure} - 36 \qquad (8)$$

where t is in minutes, and $T_{cure}$ and $T_g$ are in degrees centigrade.

For both systems, the $T_g$ calculated ($T_g$ cal) by equations 7 and 8 are included in Tables 1 and 2 together with the corresponding experimental values for $T_g$. The agreement is good.

For an approximate calculation of $T_g$ from $T_{cure}$ and cure time for the epoxy systems, only two $T_g$ vs. $T_{cure}$ lines for two specified cure times are

# END

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